PROPAGATION OF ACOUSTIC WAVES THROUGH A SPATIALLY FLUCTUATING MEDIUM: THEORETICAL STUDY OF THE PHYSICAL PHENOMENA

Gaultier Real, Xavier Cristol, Jean-Pierre Sessarego, Dominique Fattaccioli

PROPAGATION OF ACOUSTIC WAVES THROUGH A SPATIALLY FLUCTUATING MEDIUM: THEORETICAL STUDY OF THE PHYSICAL PHENOMENA.

Gaultier Real[a,b], Xavier Cristol [b], Jean-Pierre Sessarego[a] and Dominique Fattaccioli[c]

[a]Laboratoire de Mécanique et d'Acoustique (LMA), CNRS, 31 Chemin Joseph Aiguier, 13402 Marseille cedex 20, France.
[b]Thales Underwater Systems SAS, 525 route des Dolines, 06903 Sophia-Antipolis, France.
[c]Direction Générale de l'Armement – DGA Techniques navales, avenue de la Tour Royale, BP 40915, 83050 Toulon Cedex, France.

Contact author: Real Gaultier: real@lma.cnrs-mrs.fr

Abstract**:** *The authors focus on the effects of phenomena, such as linear internal waves, that are responsible for fluctuations of the depth-dependent sound speed profile and, hence, induce distortions of the resulting acoustic pressure field and degradation of the associated sonar performances. The main goal of this study is to develop a scaled experiment configuration able to provide some results representative of this kind of distortions. To do so, a theoretical study of the phenomenon has first been carried out: we obtained an expression for the standard parabolic equation applied to the Fourier transform of the moments of order 2 and 4 in 3D medium.*
Various simulation programs were developed and used for the following purposes: validating or discarding some relationships given by Flatté through his classical dimensionless analysis (ΛΦ plane); tracing rays through an acoustic lens featuring a plane face and a randomly rough face and propagating an acoustic wave through the same object in order to anticipate for the shape of the distorted pressure field, including diffraction effects.
We were able both theoretically and experimentally to induce acoustic scattering that mimics, at reduced scale and frequencies around 2MHz, the correlation properties and the corresponding array performance that would be observed at sea, after propagation through a linear internal wave field, or reflection on a rough sea surface.

Keywords: *De-coherence, Tank Experiments, Fluctuations, Dimensionless Analysis.*

1. INTRODUCTION.

Wave propagation in random media (WPRM) is a well-studied topic in the literature. From a historical point of view [1] [2], to more recent applications to various fields such as optics [3] or underwater acoustics [4] [5], it has been proven that, in order to enhance the performances of operational systems, stochastic knowledge of the fluctuating media is needed. Linear internal waves (LIW) are an example of fluctuations in the ocean medium that causes perturbations in the underwater sound propagation, such as the appearance of caustics [6].

The performance of acoustic arrays associated with this kind of phenomena is therefore mitigated [7-10]. The objective of our research is to perform measurements of sound waves fluctuations in a controlled environment (water tank), which, in our opinion, would help to understand the involved physical phenomena. In a second time, corrective signal processing techniques are sought out.

In this paper, we focus on the theoretical approach and present some simulation results compared with experimental data acquired in a tank.

2. THEORETICAL STUDY.

We first wrote the standard parabolic equation applied to the Fourier transform of the 2nd and 4th order moment of the pressure field (respectively denoted J_2 and J_4 (extension from 2D to 3D media)). These equations and the results associated (expression for the average number of eigen rays) are presented in [11].

The method we adopted for reproducing the effects of LIW like phenomena in water tanks is the propagation of an ultrasonic signal through an acoustic wax lens presenting a plane input face and a randomly rough output face. The randomly rough face of the lens is characterized by its amplitude δ_x and its vertical and horizontal correlation lengths (respectively L_V and L_H). This random profile is represented in Fig.1.

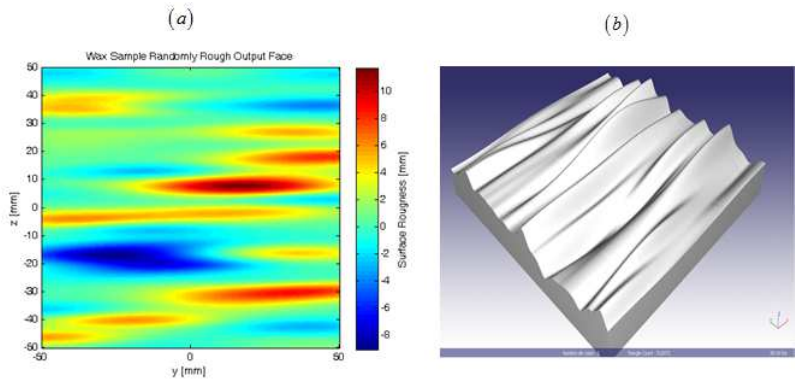

Fig.1: (a): Randomly Rough Output Face Profile - $\delta_x = 3mm;\ L_V = 3mm;\ L_H = 30mm.$*;*
(b) CAD view of the Lens.

If we can anticipate quite reasonably that our experimental configuration would induce focal points, caustics and distortions of the acoustic wave fronts, a way to link our work to the theory developed in the literature is needed. Flatté defined two dimensionless parameters in order to classify the acoustic signal distortions into perturbations regimes: the diffraction parameter Λ, qualitatively describing the nature of the acoustic distortions, and the strength parameter Φ, characterising the amplitude of these distortions. Both parameters depend upon oceanographic quantities that are measurable during at-sea experiments [4]. Unfortunately, we cannot evaluate directly these parameters with the configuration given in our experimental framework.
Flatté proposed connections between these two parameters and the average number of eigen rays $\langle N_{eig} \rangle$, the rms phase difference between the extreme micropaths $\Delta_{\varphi RMS}$ and the total vertical range over which the micropaths are spread Δ_z [4]:

$$\Lambda\Phi \approx \langle N_{eig} \rangle \quad (1), \qquad \Lambda\Phi^2 \approx \Delta_{\varphi RMS} \quad (2), \qquad \Lambda\Phi \approx \frac{\Delta_z}{L_V} \quad (3)$$

Our first goal was therefore to validate these equations: we developed a simulation ray tracing program in order to assess the parameters involved in the right members of equations (6) to (8) in the case of a medium presenting Gaussian fluctuations of the sound speed. The software is based on tracing rays and takes into account the local sound speed fluctuations. The ray tracing system from [12] is solved using a 5th order Runge-Kutta technique [13].

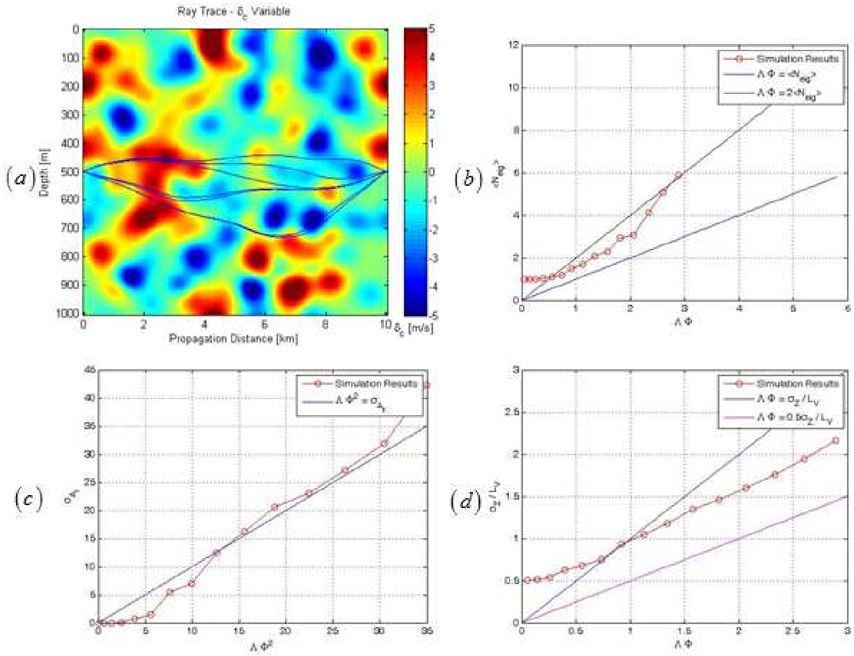

Fig.2: (a): Ray Trace - Medium Presenting Fluctuations of the Sound Speed - f=1kHz – z_S=500m - 404m <z_R< 596m - 1 km<d_x< 15km – L_V=50m – L_H=500m – δ_c=1m/s.
(b) to (d): Equation (6) to (8) Validation.

Fig.2 shows a relatively good agreement between our simulations and Flatté's identities corresponding to equations (6) to (8). All three relations can be validated and used in the following work.

3. SIMULATION RESULTS.

3.1. RAY TRACING AND Λ-Φ PLANE.

With the ray tracing program, it was possible to predict the average number of eigenrays $\left\langle N_{eig} \right\rangle$ and the rms phase difference between extreme micropaths $\Delta_{\varphi RMS}$ when a beam of rays propagates through the wax lens defined earlier. These predictions were conducted for several positions of the sensor used as a receiver. The distance between the source and the object is also a tunable parameter. Therefore, we were able to evaluate $\left\langle N_{eig} \right\rangle$ and $\Delta_{\varphi RMS}$ for virtual arrays (either vertical or horizontal) at various distances of the distorting object.

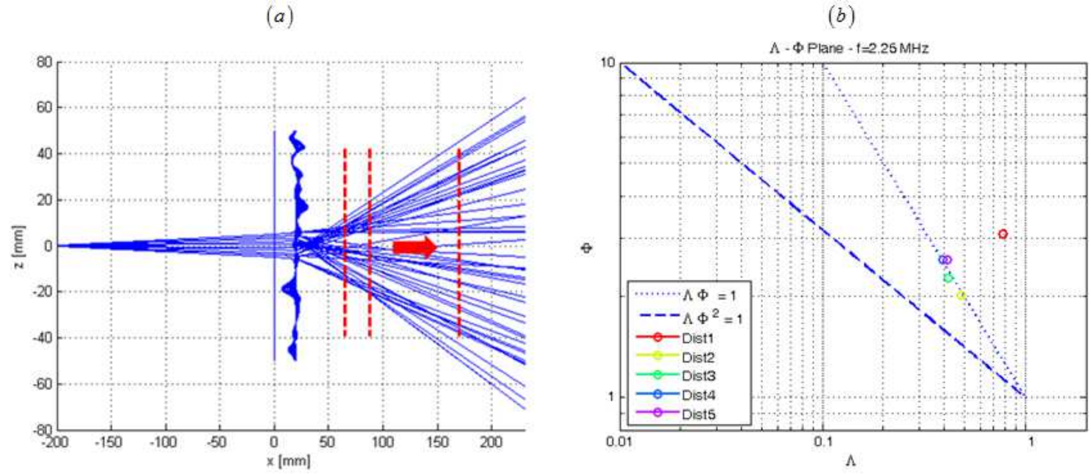

Fig.3: (a): Ray Trace – Vertical Direction – Wax Lens.
(b): ΛΦ Plane – 256 Sensors Vertical Array – f=2.25MHz.

The analysis of Fig.3 shows that this process provides results in the fully saturated regime at distance 1, and partially saturated regime for all other distances, in the case of a vertical linear array. This is consistent with the presence of caustics at very short distance from the lens output face.

3.2. ACOUSTIC WAVE PROPAGATION.

Moreover, in order to anticipate for experimental results in terms of the shape of the acoustic field measured after propagation through a distorting surface, we developed a 3D propagation software based upon a parabolic equation calculating the propagated acoustic wave in an unbounded medium. Hence, we are able to observe the distorted acoustic field in various planes.

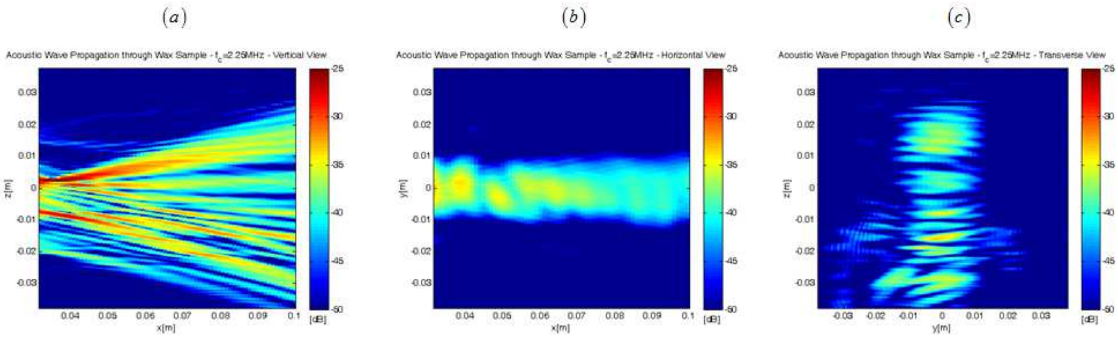

Fig.4: Acoustic Wave Propagation Through Wax Lens: (a): Vertical Plane – (b) Horizontal Plane – (c) Transverse Plane.

The refraction of the acoustic wave can be observed in Fig.4, especially in the vertical case (Fig.4 (a)), where caustics can be observed in good agreement with Fig.3 (a).
Finally, we compared the coherence function calculated with the output of the simulation program presented in Fig.4 with experimental results of the same configuration.

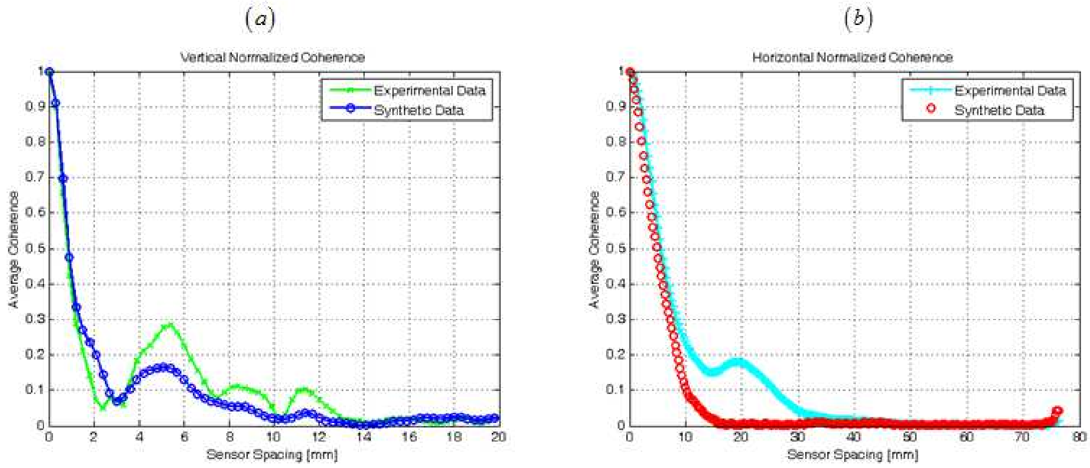

Fig.5: Average Coherence - (a): Vertical Array – (b) Horizontal Array.

Fig.5 displays the average coherence function along the linear array for the first propagation distance ($d_{src/rcvr} = 0.23\,m$).The agreement between the two cases is quite good for the main lobe, and therefore for the radius of coherence, whose value can be related to the array gain [8].

4. CONCLUSION

The theoretical and simulation results presented here are used to define an experimental protocol leading to the acquisition of distorted acoustic signals in specific regimes of fluctuations predicted according to Flatté's theory. The induced distortions in the acoustic field are characteristic of ocean perturbations, such as LIW. The effect of these perturbations on array gains is studied through the calculation of the coherence function. The latter displays a small radius of coherence both in experimental and simulation framework, which implies a degradation of the system performances.

ACKNOWLEDGMENT

This work is sponsored by a research grant of the Mission pour la Recherche et l’Innovation Scientifique (DGA – MRIS), the Laboratory of Mechanics and Acoustics (LMA – CNRS) and Thales Underwater Systems.

REFERENCES

[1] I. Newton, “Opticks”, Fourth Edition, 1704.
[2] V. I. Tatarskii, “The effects of the Turbulent Atmosphere on Wave Propagation”, Keter Press, Jerusalem, 1971.
[3] S. A. Metchev, L. A. Hillenbrand, and R. J. White, “Adaptive optics observations of vega: eight detected sources and upper limits to planetary-mass companions”, The Astrophysical Journal, 582(2):1102, 2003.
[4] R. Dashen, W.H. Munk, K.M Watson and F. Zachariasen, “Sound Transmission Through a Fluctuating Ocean”, Cambridge University Press, 1979.
[5] S.M. Flatté, “Wave Propagation Through Random Media: Contributions from Ocean Acoustics”, Proc. Of the IEEE, 71(11), 1267-1294, 1983.
[6] WH Munk and F Zachariasen, “Sound propagation through a fluctuating stratified ocean:Theory and observation”, The Journal of the Acoustical Society of America, 59:818, 1976.
[7] R. Laval and Y. Labasque, “Medium Inhomogeneities and Instabilities: Effects on Spatial and Temporal Processing”, Underwater Acoustics and Signal Processing, 41-70, Springer Netherlands, 1981.
[8] E. Y. Gorodetskaya, A. I. Malekhanov, A. G. Sazontov, and N. K. Vdovicheva, “Deep-water acoustic coherence at long ranges: Theoretical prediction and effects on large-array signal processing”, Oceanic Engineering, IEEE Journal of, 24(2):156-171, 1999.
[9] D. Fattaccioli and X. Cristol, “Degradation of Sonar Processing Performances in Random Fluctuating Environments”, Proceedings of D. Weston Symposium on Validation of Sonar Performance Assessment Tools, Clare College, Cambridge, UK, 7-9 April 2010.
[10] X. Cristol, D. Fattaccioli and A.S. Couvrat, "Alternative criteria for sonar array-gain limits from linear internal waves", Proceedings of ECUA 2012 (European Conference on Underwater Acoustics), Edimburg, UK, 2-6 July 2012.
[11] G. Real, J.-P. Sessarego, X. Cristol and D. Fattaccioli, “Experimental Study of the Influence of Spatial Inhomogeneities in Underwater Acoustic Propagation”, Proc. Of the 1st Underwater Acoustic Conference, Corfu, GREECE, 23-28 June 2013.
[11] A. D. Pierce, “Acoustics: an introduction to its physical principles and applications”, McGraw Hill, 1981.
[12] E. Hairer, S. P. Norsett, and G. Wanner, “Solving Ordinary Differential Equations I :Nonstiff Problems”, 2nd Edition, Springer Verlag, 2000.